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COVERING SHOCK WAVES ON MARS INDUCED BY INSIGHT'S HP^3-MOLE - EFFICIENT CO-SIMULATION USING DEM AND MULTI-DOMAIN DYNAMICS

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Abstract. NASAs discovery mission InSight (Interior Seismic Investigations, Geodesy and Heat Transport) scheduled for launch in 2018 will investigate the interior of Mars. For the subsurface locomotion, DLR's self-impelling nail nicknamed the "Mole" needs to hammer itself down to 5 m into the martian soil with less than 5 W of input power. A major focus during the Mole's development has been on simulation and analysis using virtual prototypes. As certain aspects of the environmental conditions on Mars cannot be recreated and tested on earth, high-fidelity coupled simulations are required to achieve the accuracy needed. These co-simulations are composed by a multi-body based cross domain model for the hammering device and a discrete element model for the soil. The article focuses on the coupling strategy of both models as well solutions in terms of communication. Furthermore efficiency improvements of the computationally expensive DEM models will be presented. Using these approaches the detailed stroke cycle and shock wave propagation are analyzed. Allowing to evaluate the performance under martian or terrestrial conditions.

1 INTRODUCTION

The question for the formation of our solar system is one major driver of science. Hence NASAs discovery mission InSight (Interior Seismic Investigations, Geodesy and Heat Transport) [1] aims to gather knowledge about Mars' interior structure. Therefore DLR's HP^{3}instrument (Heat Flow and Physical Properties Package) [2] measures the internal martian heat flux in a total depth of 5 m. Thus, its locomotion system, the self-impelling nail nicknamed the "Mole" needs to hammer itself into the martian soil with less than 5 W of input power.
The HP^{3}Mole's development has been supported by simulations since the very beginning,

as certain environmental aspects cannot be covered in terrestrial test setups. The most precise of the models for the HP^{3}Mole is a coupled simulation of a multi-body based cross domain model for the hammering device itself and a discrete element model for the soil. Thereby the first covers the dynamics of the mechanism in several domains within the multi-body framework using a single solver. The surrounding soil is covered by the particle simulation framework DEMETRIA [3] based on Pasimodo [4]. As the effects of the two main domains happen in different timescales, dedicated solvers and communication strategies need to be applied in order to ensure proper data exchange and numerical stability. One further important point is to speed up the computationally expensive DEM model in order to allow for simulations usable in the limited development time frames of low-cost planetary missions.

2 HP^{3}Mole for InSight

DLR's HP^3-Mole is designed as an efficient low-velocity penetrator [2]. An impact driven locomotion has been chosen and the Mole is equipped with an internal hammering mechanism, periodically loaded by a DC-Motor. In order to fullfill its scientific task of measuring thermal properties of the red planet's interior, the Mole is equipped with three scientific payloads: STATIL (Static Tilt Measurement Unit), TEM-A (Thermal Excitation Measurement Active) and TEM-P (Thermal Excitation Measurement Passive), whereby the first two are integrated into the Mole's housing and the latter is included in the science tether dragged behind the Mole. Fig. 1 shows the internals of the Mole, whereas the hammering mechanism is situated in the front part and the payload compartment is seated in the rear section.

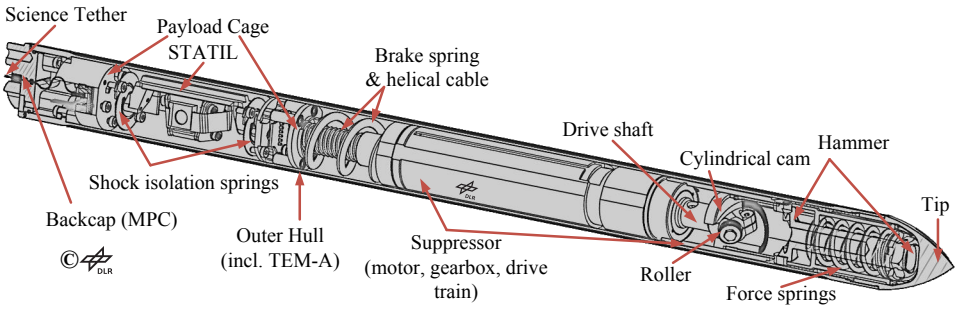

Figure 1: Cut through the flight model generation (PFM/PFE) of the HP^3-Mole , cf.[6]

During the tensioning process, the force spring is periodically loaded due to the drive-shaft roller running up on the cylindrical cam. Once the top of the cam is reached, the hammer is released and the fully loaded force spring it towards the tip. Meanwhile the heavier suppressor mass is accelerated towards the payload compartment. In order to allow the Mole to work as a "mechanical diode", mitigation of the upwards forces takes place by suspending the suppressor on a brake spring. This spring is thereby designed to distribute the suppressor energy over an extended intervall of time, never exceeding the

anisotropic friction forces between the soil and the outer hull surface. During impact of the hammer on the tip, energy is transmitted to the outer hull and the Mole moves into the soil until it is stopped by its resistive forces. Once the suppressor movement reversed due to brake spring and gravity, it moves towards the tip and causes a second major stroke in the same stroke cycle [3, 9, 6]. Due to several subsequent rebounds of hammer and suppressor additional major and minor strokes are carried out. These additional strokes mainly affect the dynamic behaviour of the Mole inside the soil [3, 9, 6].

3 MODELING

Modeling and simulation have been crucial for the development of the HP^{3}Mole. With InSight being a low-cost mission, the number of physical prototypes of the Mole were limited as well as the possibility for risky tests using them. Thus most situations have first been evaluated using virtual prototypes in simulation. Ofttimes the simulation even gave green lights for a risky test in advance. In order to use such simulations as a substitute for real prototypes, high-fidelity models are needed. Therefore high-precision soil models described in [3, 5, 6, 8] have been developed and have also been used to create fast but still precise single point models [11, 3]. Yet precise soil models alone are not sufficient to cover the mutual influences on the dynamics of the mechanism and the soil. Thus an additional cross domain model based on enhanced multi-body dynamics has been developed [3, 6]. The two major models have then been coupled in a co-simulation using the DLR-SR framework DEMETRIA.

3.1 Cross Domain Mechanism Model

To accurately model the behavior of the mechanism several domains must be covered: [9, 11]:

- dynamics and kinematics of mechanisms internal bodies,
- tensioning and release of the force spring including the DC-motors electro-dynamics,
- contact dynamics for the impact driven energy transmission,
- force as well as brake spring including stiffness-contributing parts,
- conditions on Earth and Mars: atmospheric conditions, temperature and gravity,
- critical frictional effects,
- gas flow and pressure distribution in the Mole modeled by dyn. pneumatic networks,
- dynamics and influence of the spring suspended payload STATIL,
- and the modular definition of outer forces (test stands, soil models incl. DEM).

Thereby one key goal is to use as little simulator coupling as possible. Extensive coupling would cause overhead on preprocessing and is prone for numerical problems. Thus all the different physical domains of the mechanism model have been included into the mutli-body system software Simpack. This allows for the use of a single solver and time step size. Validation of the mechanism model is shown in [6, 3].

3.2 Discrete Element Model Soil Modeling

The soil models for the most precise models of the HP^{3}Mole are discrete element models. DEM discretizes the simulation domain by distinct particles, generating a naturally discontinous model of granular matter. Even though computation power heavily increased over the course of the last years, modern computers are still not capable of modeling large scale domains with physical grains sizes. Because of that and due to the focus on workstation computers DEMETRIA uses up-scaling of the particle size according to the tool resolution. Further detail on the calibration-free model parametrization is given in [8].
In DEMETRIA models are divided into three different layers of scale . Regarding overall simulation performance, the macroscopic and mesoscopic layer give the highest potential for speed up, mostly limiting the number of particles included in the model. Thus this article will focus on the macroscopic and mesoscopic layer, whereas the the microscopic layer, covering grain shape, contact models etc., is described in [5, 8, 3].
On mesoscale, boundary and symmetry conditions as well as domain size are most impor-

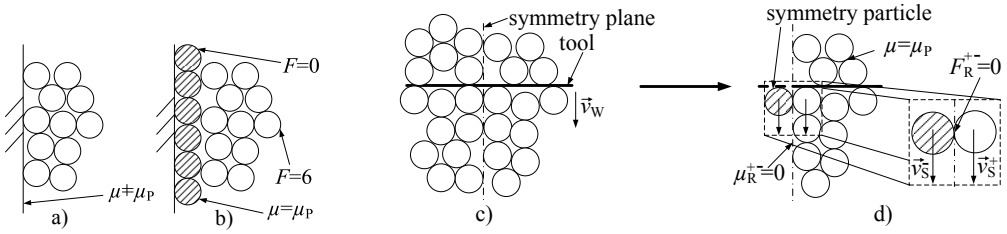

Figure 2: Basic scleronomic boundary conditions: smooth boundary a) and rough boundary b), symmetry condition c), full domain vs. symmetry, d) effects on the symmetry plane, cf. [3]

tant in order to have efficient but yet accurate simulations. The basic boundary conditions are given as scleronomic boundaries. The most simple condition is the smooth boundary mimicking a physical boundary, i.e. a container wall. It is composed by triangulated surfaces possessing the friction parameters of the physical friction pairing. In most cases the simulation domain does not need to have the full extension of the physical container [3]. Once $E_{\mathrm{kin}} \to 0$ is met, the additional particles do not increase accuracy anymore and the simulation domain may be shrunk. In order to cover the correct frictional behaviour including form closure, the rough boundary (Fig. 2) has to be used if the domain size is limited and $E_{\mathrm{kin}} \to 0$ is ensured. It consists of fixed particles possessing interparticle friction, acting as a non moving layer of particles [3]. Symmetry is a special condition, helping to shrink the domain even further. As the symmetry plane always has to cut the domain through the tool, the velocity $\vec{v}_{\mathrm{S}}$ on the left and right hand side of the symmetry plane yields [3]:

$$|\Delta\vec{v}_{\mathrm{S}}| \to 0 \;\forall\; \Delta\vec{v}_{\mathrm{S}} = \vec{v}_{\mathrm{S}}^{+} - \vec{v}_{\mathrm{S}}^{-};\; \wedge\; |\vec{v}_{\mathrm{S}}^{+}| \cong |\vec{v}_{\mathrm{S}}^{-}|; \tag{1}$$

Thus between neighboring particles right at the symmetry plane no frictional forces are present. Hence the following assumption is valid for the frictional interface [3]:

$$|\vec{F}_{\mathrm{R}}^{+-}| = 0 \rightarrow \mu_{\mathrm{R}}^{+-} = 0 \tag{2}$$

Symmetry can either be either plane or rotation symmetric, whereas the extreme cases of these symmetries yield a 2D representation. For the both cases the forces and torques acting on the tool need to be corrected. Details on the correction are given in [3].

In order to increase the performance beyond the usage of symmetry conditions, especially for moving tools, dynamic boundaries may be applied. These boundaries are basically moving the domain together with the tool by constantly loading and deleting particles. The basic principle in 1D and the algorithm to be applied are shown in Fig. 3. Loading of new particles only occurs every n simulation time steps in order to minimize the overhead by memory latency. If particles would be loaded from hard disk rather than main memory n has to increase significantly and loading is only viable for slow movement speeds. Hence only main memory shall be used for loading. As in DEM the particle inventory usually only features values of t and $t-\Delta t$ the older values are stored in a special memory particle [3]. The amount of particles to be loaded is determined by membership functions based

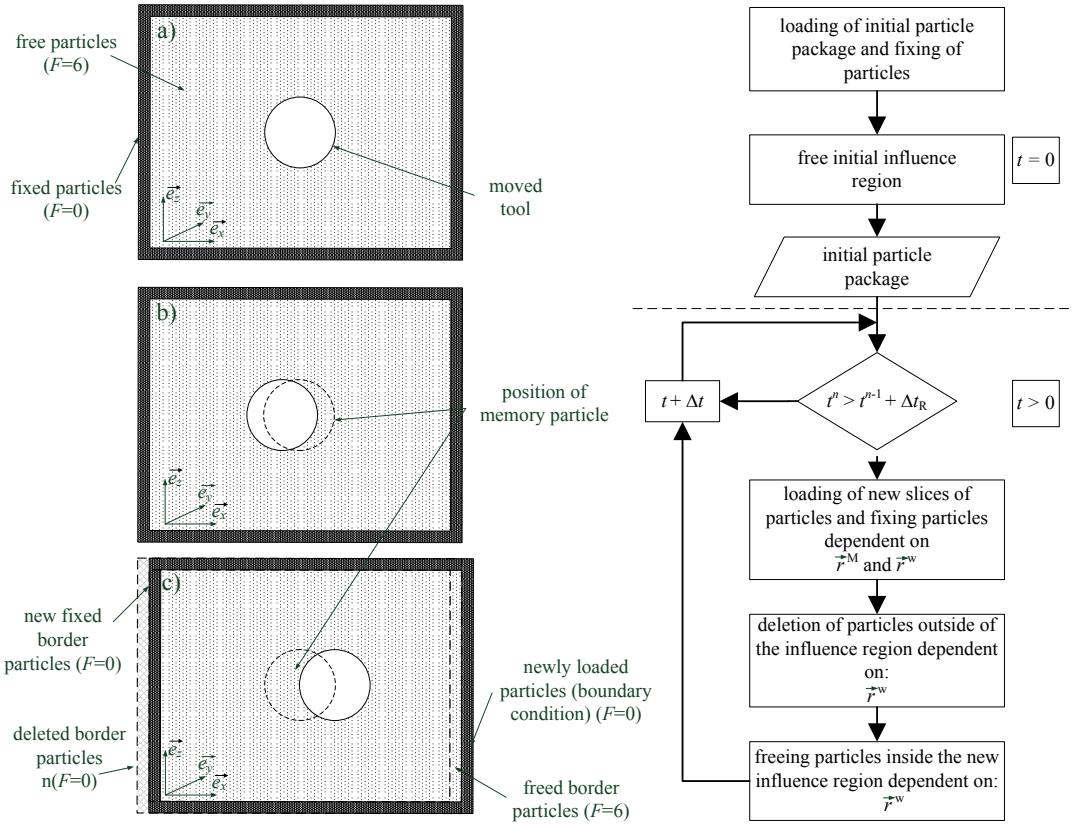

Figure 3: Basic strategy for dynamic boundaries in one dimension, cf. [3]

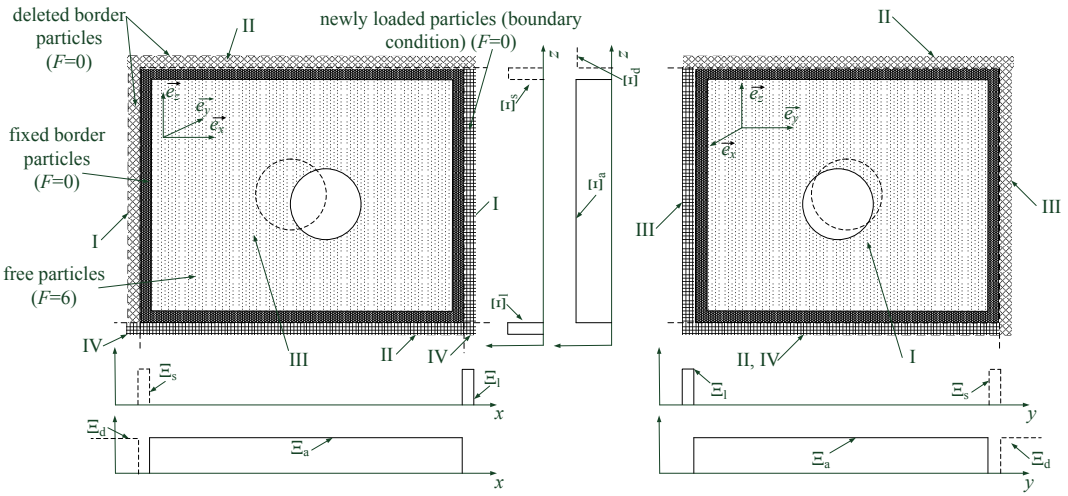

Figure 4: Three dimensional dynamic boundaries with membership functions, cf. [3]

on the influence region of the tool. For full three dimensional the membership functions are visualized in Fig. 4. If the membership function equals 1 then the particle is member of the respective group. The HEAVISIDE membership functions Ξ_{init} (initial package), Ξ_{a} (activating), $\vec{\Xi}_{\text{d}}$ (deletion), Ξ_{s} (fixing) and Ξ_{l} (loading) evaluate to (cf. [3]):

$$\Xi_{\text{init}}(\vec{r}^{\,\text{p}}, \vec{r}^{\,\text{w}}) = \prod_{i=1}^{3}\prod_{h=1}^{2}\Xi_i\Big(\Big(r_i^{\text{p}} - (r_i^{\text{w}} - n_{i,h}^0 r)\Big)\cdot(-1)^{h+1}\Big);\ F_{\text{p}} = 0 \tag{3}$$

$$\Xi_{\text{a}}(\vec{r}^{\,\text{p}}, \vec{r}^{\,\text{w}}) = \prod_{i=1}^{3}\prod_{h=1}^{2}\Xi_i\Big(\Big(r_i^{\text{p}} - (r_i^{\text{w}} - (n_{i,h}^0 - 3)r)\Big)\cdot(-1)^{h+1}\Big);\ F_{\text{p}} \neq 0 \wedge n_f = 3 \tag{4}$$

$$\Xi_{\text{s}}(\vec{r}^{\,\text{p}}, \vec{r}^{\,\text{w}}) = \prod_{i=1}^{3}\prod_{h=1}^{2}\Xi\Big(\Big(r_i^{\text{p}} - (r_i^{\text{w}} - (n_{i,h}^0 - 6)r)\Big)\cdot(-1)^{h+1}\Big);\ F_{\text{p}} = 0 \wedge n_f = 3 \tag{5}$$

$$\vec{\Xi}_{\text{d}}(\vec{r}^{\,\text{p}}, \vec{r}^{\,\text{w}}, \dot{\vec{r}}^{\,\text{w}}) = \prod_{h=1}^{2}\vec{\Xi}\Big(\Big(\vec{r}^{\,\text{p}} - (\vec{r}^{\,\text{M}} - (\vec{n}_h^0 + 5)r)\Big)\cdot(-1)^{h+1}\Big)\vec{\Xi}\Big(\dot{\vec{r}}^{\,\text{w}}\Big) \tag{6}$$

$$\begin{aligned}\Xi_{\text{l}}(\vec{r}^{\,\text{p}}, \vec{r}^{\,\text{w}}, \dot{\vec{r}}^{\,\text{w}}) = \sum_{i=1}^{3}\prod_{h=1}^{2}&\Xi\Big((-1)^{h+1}(r_2^{\text{M}} - r_2^{\text{p}} + n_{2,1}^0 r)\Big)\Xi\Big((-1)^{h+1}(-r_2^{\text{p}} - r_2^{\text{M}} + n_{2,1}^0 r)\Big)\\ &\cdot\Xi_i\Big((-1)^{h+1}(r_i^{\text{p}} - r_i^{\text{M}} + n_{i,1}^0 r)\Big)\Xi_i\Big((-1)^{h+1}(r_i^{\text{w}} - r_i^{\text{p}} + n_{i,1}^0 r)\Big)\\ &\cdot\Xi_i\Big((-1)^{h+1}\dot{r}_i^{\,\text{w}}\Big);\quad |\dot{\vec{r}}^{\,\text{p}}| = 0 \wedge |\vec{\omega}^{\text{p}}| = 0 \wedge F_{\text{P}} = 0\end{aligned} \tag{7}$$

with $\vec{r}^{\,\text{p}}, \vec{r}^{\,\text{w}}$ the position vector of particle and tool, F_{P} the particles DOF and $\underline{n}^0$ the influence region matrix.

The macroscale is containing the description of the interaction of locomotion gear, i.e. the Mole's outer hull and the particles themselves. The hull is modeled as a smooth triangulated mesh featuring the friction parameters of the real hull to the regolith. The mesh is discretized equidistantly in polar coordinates and composed by a parametric description, allowing for automated variation of the outer shape in optimization runs. Due to the simplicity of the equation for the cylindrical part, only the vertex' $\underline{P}_{\mathrm{vT}} = (x_{\mathrm{vT}} \quad y_{\mathrm{vT}} \quad z_{\mathrm{vT}})$ of the Mole tip in cartesian coordinates need to be computed by mathematical bending [3]. The Mole's hull is then composed from the tip $\underline{P}_{\mathrm{vT}}$, hull $\underline{P}_{\mathrm{vZ}}$ and back cap $\underline{P}_{\mathrm{vMPC}}$ vertices [3]:

$$\underline{P}_{\mathrm{vH}} = \left(\underline{P}_{\mathrm{vT}}^{\mathrm{T}} \; \underline{P}_{\mathrm{vZ}}^{\mathrm{T}} \; \underline{P}_{\mathrm{vMPC}}^{\mathrm{T}}\right)^{\mathrm{T}};\; \underline{P}_{\mathrm{vH}} \in \mathbb{R}^{3\times(n+m+l)}, \underline{P}_{\mathrm{vT}} \in \mathbb{R}^{3\times n}, \underline{P}_{\mathrm{vZ}} \in \mathbb{R}^{3\times m}, \underline{P}_{\mathrm{vMPC}} \in \mathbb{R}^{3\times l}$$

In order to model the Mole's dynamics the co-simulation port of Pasimodo [4] is used and the mesh is moved according to the positions received via TCP/IP.

4 CO-SIMULATION

In order to setup the co-simulation pre-existing interface of Pasimodo and Simpack are used. For ease of application Matlab is used as moderator between the two clients [3]. In order to have a fully automated coupling of the tools, all three are wrapped into the DLR-SR Particle simulation framework DEMETRIA. In the following sections the procedure of DEM-MBS coupling in DEMETRIA is explained.

4.1 Coupling of the Tools & Communication

One of the main goals of DEMETRIA is to provide automated simulation setups, ready for variational or optimization runs. Thus DEMETRIA sets up the communication between the different tools, by searching for free ports, blocking them. Once this is done, the clients are started and put into a listening state as shown in Fig. 5. Upon the clients signaling readiness, the server (Matlab) is started, causing the instantaneous start of the coupled simulation [3]. In order to provide stable numerical behaviour, as well as to gain best performance, each client utilizes a specialized integration scheme. The time step size Δt for the particle simulation is thereby chosen as the maximum stable step size for the Newmark-β scheme. As the particle simulation has a much longer per step work load, the step size of the MBS may be chosen below the maximum stable time step, allowing for the observance of higher frequency results. This is especially important for the HP^{3}Mole, as the impact driven energy transmission requires time steps in the range of $[10^{-9}, 10^{-7}]$s. Thus the soil force is held constant for n MBS steps until the next DEM time step is completed. Thus the DEM time step size is also used as communication step size in Matlab utilizing a fixed step discrete scheme. In Fig. 5 the time steps and communication points are visualized. Once a co-simulation job is started and further licenses are available, DEMETRIA's job control allows for additional simulations running in parallel [3].

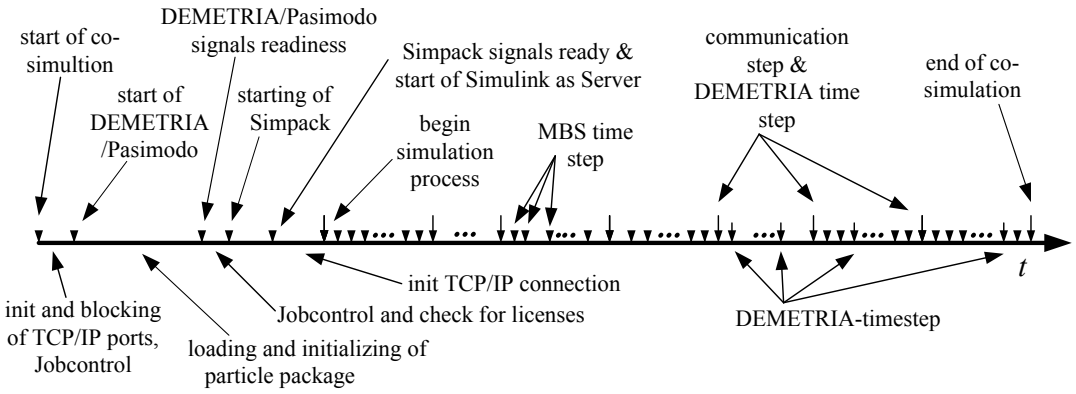

Figure 5: Communication time line for preprocessing and co-simulation, cf. [3]

4.2 Preparation of the Co-Simulation

In order to allow for coupled simulations of the Mole's hammering the particle package needs to be initialized. This is achieved by depositing the particles due to gravity. Once a package has reached equilibrium state, it might be subject to co-simulation or further parameter changes - the latter requiring one more relaxation run. As the Mole is a low velocity penetrator [7], simulating the full depth progress in co-simulation is not feasible in finite time horizons. As shown in Fig. 6 it is valid to drive the Mole's hull rheonomically to the depth of interest. Due to the dynamic boundaries the number of particles is held nearly constant and the layers of locked particles preserve the overburden pressure. Once the hull reached the final depth, the package needs to be relaxed again, as the Mole features one hammering cycle every 3.8 s, only [3]. Thereafter the full co-simulation is carried out for the detailed analysis of a single stroke as shown in Fig. 6. Concluding the full process, one full co-simulation cycle takes one upt to three days of CPU time.

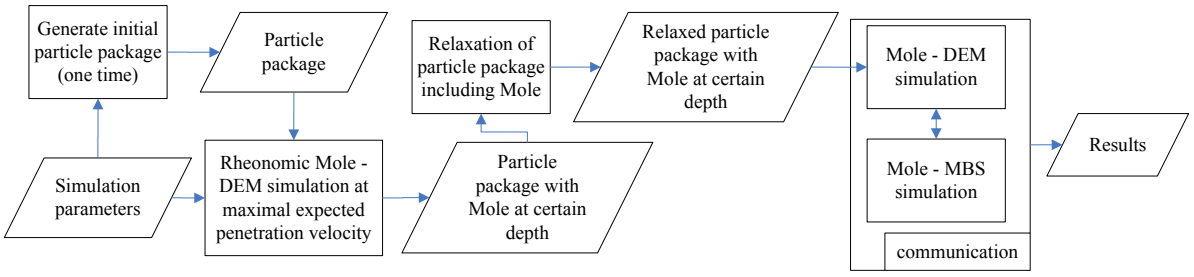

Figure 6: Preparation and procedure of the co-simulation, cf. [3] and [6]

5 ANALYSIS & RESULTS

The co-simulation method developed above has been used intensively to analyze and improve the Mole. The following sections will give a short overview on the results that have been gathered using the simulations. Details on the analysis are given in [6, 9, 3, 11].

5.1 Validation & Verification

The evaluation of the simulations accuracy has been carried out in a three staged process: at first the mechanism model has been validated using different Moles on a health check test stand comparing the Moles transient motion on the teststand, second the soil model has been checked against penetrometer and bevameter measurements comparing stresses and last the full co-simulation has been validated. This full system validation was done with simple and deep penetration tests using flight-like Moles. Thereby the penetration performance, the timing of effects as well as high-speed camera data and x-ray videos have been used. The final evaluation showed less than 16% of error for penetration depth of the complex coupled simulation, whereas low errors in literature range about 30-50%. Details on the validation process can be found in [6, 3].

5.2 Variation of the Outer Shape

Using the HP^{3}Mole co-simulation it is possible to conduct analysis of the mutual influence between soil and mechanism dynamics. Such analysis are not possible using the real prototype and hence the simulation enhances the understanding and development of the mechanism extensively. An example application of the Mole co-simulation is the analysis of the influence of tip geometry on the locomotion performance [9]. As shown in Fig. 7 (left) the shape mainly influences the direction of soil displacement and thus of the propagated wave. Comparisons of the resistive forces of different tips show, that neglecting friction sharper tips gain better performance. Thus a compromise of tip resistance, frictional forces and tip size have to be taken into account for the development. Furthermore the simulations show, that for non-conical tip shapes, quasi static resistance may differ significantly from dynamic resistance during hammering. Thus a final comparison using a full co-simulation is essential. Fig. 7 (right) shows the resultant penetration depths over

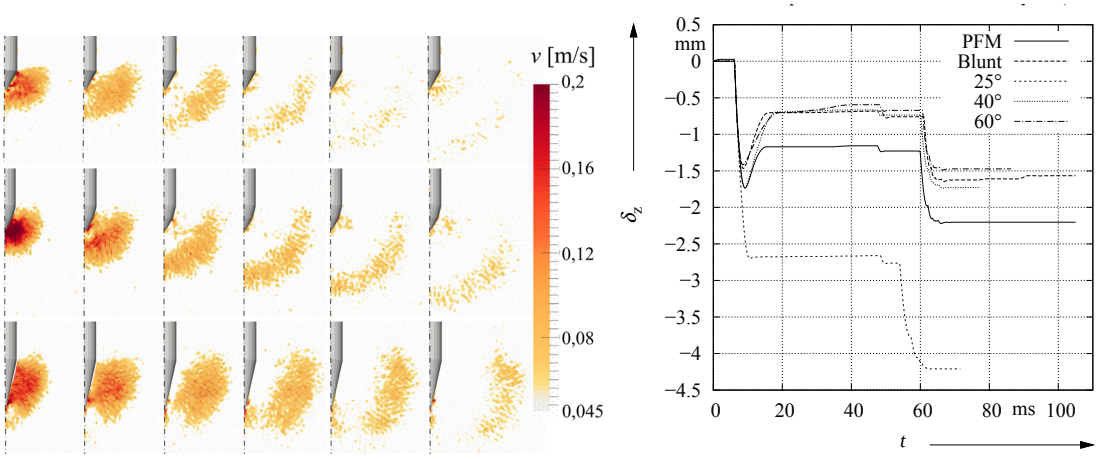

Figure 7: Wave propagation through the soil 2-7 ms for different tip shapes of the HP^{3}Mole (left) and the corresponding penetration depth (right), cf. [3], [9]

one stroke cycle [3]. For conicial tips it is obvious, that the more radial displacement of the soil visible in Fig. 7 (left) allows for higher penetration depth and less elastic rebound due to reflow waves in the soil. Regarding the reflow waves, more radial reflow causes less rebound but higher normal forces on the cylindrical part of the hull and thus higher friction, lowering possible rebound even further.
When non-conical tips are taken into account the actual non-linear shape greatly influences the performance. Comparing the PFM (Protoflight Mole) and Blunt (bullet shape) tip, it is obvious, that the PFM tip outperforms the equally long Blunt tip. They perform similar up to the end of the first stroke, but the Blunt tip then causes higher rebound due to less radial soil displacement. Compared to the conical tips, the PFM tip also outperforms a 40° tip while having the length of a shorter 50° tip. Further analysis for the variation of the outer shape can be found in [9, 3].

5.3 Shock Wave Propagation caused by the Mole - Earth vs. Mars

Shock wave propagation and the shape of the velocity field inside the soil is fairly important for the Mole's locomotion. Propagating waves mostly into vertical direction rather than radially, would cause compaction in front of the Mole's tip and thus the mechanism would increase compaction along the way, impeding its own movement. Regarding the previous sections results, a sharper tip would be most beneficial, keeping in mind the higher drag due to frictional forces. In planetary exploration mass and space budget is limited and thus an experience based trade of between tip length and resistance led to the non-linear shape of the PFM-tip implemented in the flight model. For the Mole development, both martian and terrestrial environment have to be taken into account in simulation in order to extrapolate the terrestrial tests to Mars. Fig. 8 shows the velocity profile of the particles for the Mole with the PFM-tip on Earth and on Mars. Comparing the two different environments, more particles are influenced at higher velocities on Mars, which is especially visible in front of the tip. This difference is caused by the lower gravity of $g = 3.69\,\mathrm{m/s^2}$, as it decreases bulk density with a lower coordination number of the package, which again lead to decreased overburden pressure and thus lower shear strength. The different behaviour at the Mole back cap can also be explained by this effect: Due to lower gravity the particles on top of the Mole experience lower accelerations due to gravity and overburden pressure and thus show lower velocities while closing the cavity towards the Mole. The maximum penetration depth on Mars in 1 m of depth is about 2.8 mm per stroke cycle given the HP^{3}reference simulant. Further results and detailed analysis of the mechanisms stroke cycle can be found in [6, 9, 3, 11].

6 CONCLUSIONS

In this article a method to model the complex behaviour of the HP^{3}Mole using coupled mixed domain models has been proposed. As a special focus methods to improve the performance of the computationally expensive DEM simulations of the soil have been

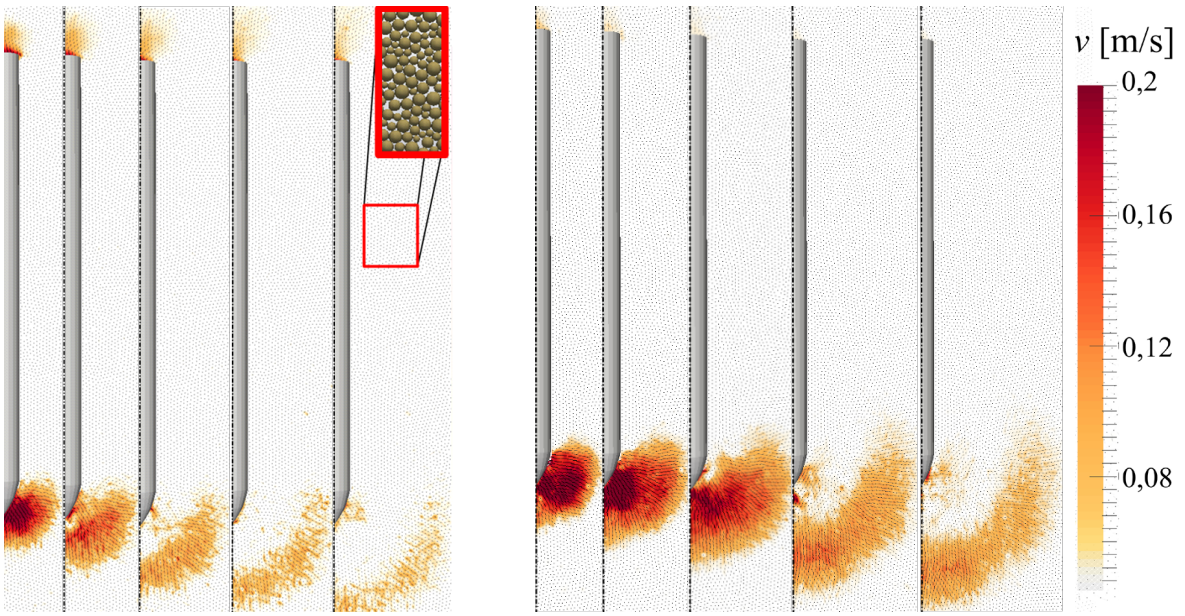

Figure 8: Wave propagation through the soil 2,3,4,6 and 7 ms after the first stroke of the HP^{3}Mole's hammering cycle on Earth, cf. [3], [9] and [6]

given, while maintaining sufficiently high accuracy for critical applications in planetary exploration missions. These improvements were mainly implemented in the mesoscopic layer of the modeling, e.g. by introduction of dynamic boundaries. Furthermore the co-simulation approach using the DLR-SR framework DEMETRIA, focusing on automated simulation cycles has been introduced. Therefore special issues in terms of communication have been discussed. Some of the applications that arose during the development of the HP^{3}Mole's flight hardware have been shown and range from in depth analysis of the stroke cycle and soil wave propagation to optimization and applications in planetary science.
A major limitation of the models is the needed runtime of 1 up to 3 days per stroke cycle and depth. Thus the results and knowledge gathered are used to develop simpler and faster models to allow for mechanism optimization and short term reactions on possible investigations required during the mission after landing on Mars in 2018.
In future work the model will be applied to further research on performance optimization of hammering mechanisms for future missions. The models and their simpler derivatives will be used to analyze the mechanical soil properties of martian regolith in-situ after landing in Elysium Planitia.

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